Journal of Animal Environment

(E-ISSN 2717-1396, ISSN 2717-1388)

Original Research Paper

Climate Change and Shifting Pest Dynamics: Implications for Sustainable Agriculture and Crop Protection

Kunal Dhaku Jadhav[1], Ketaki Naik[2], Bhvishka Sugandh[3], Priyanka D. More[4], Varsha Yadav[5], Mamta Rana[6]

[1]lifelong Learning and Extension, University of Mumbai, Maharashtra, India.

[2]Department of Artificial Intelligence and Machine Learning, Bharati Vidyapeeth's College of Engineering for Women, Pune.

[3]VMV Commerce JMT Arts & JJP Science College, Nagpur, Maharashtra 440008, India

[4]Department of Computer Science Engineering -Data Science, Vishwakarma Institute of Technology, Pune-411048, India

[5]Department of Computer Science and Engineering Rungta College of Engineering and Technology, Rungta International Skills University Bhilai Chhattisgarh,490024 India

[6]Department of Environmental Studies, Satyawati College, University of Delhi

jdkunal@mu.ac.in[1], ketaki.naik@bharatividyapeeth.edu[2], bhvishkasugandh@gmail.com[3], priyanka.more@vit.edu[4], varsha.yadav@rungta.org[5], mamtarana@satyawati.du.ac.in[6]

Abstract

Climate change is significantly altering agricultural ecosystems by influencing the distribution, development, reproduction, migration, and seasonal activity of crop pests. Rising temperatures, changing rainfall and humidity patterns, warmer winters, droughts, and extreme weather events can modify pest life cycles and enable the expansion of pest populations into previously unsuitable regions. These changes increase the probability of emerging and invasive pest outbreaks, alter pest–crop interactions, and disrupt relationships between pests and their natural enemies. Consequently, shifting pest dynamics can contribute to crop yield and quality losses, increased pesticide dependence, higher production costs, environmental degradation, and risks to food security. This paper examines the influence of major climatic factors on pest ecology and evaluates their implications for sustainable agriculture and crop protection. It further discusses climate-resilient management approaches involving integrated pest management, biological control, resistant crop varieties, crop diversification, and climate-smart agricultural practices. The potential of artificial intelligence, remote sensing, Geographic Information Systems, Internet of Things-based monitoring, and predictive early-warning systems for improving pest surveillance and risk assessment is also highlighted. The study emphasizes an integrated approach combining ecological management, climate information, digital monitoring, and predictive analytics to support timely and targeted pest interventions. Such strategies can reduce unnecessary pesticide use, improve agricultural resilience, and contribute to environmentally sustainable crop protection under changing climatic conditions.

Keywords: Climate Change, Pest Dynamics, Sustainable Agriculture, Crop Protection, Integrated Pest Management, Pest Forecasting, Artificial Intelligence, Climate-Smart Agriculture.

***Corresponding Author:**

Received: 25th July, 2026 | Revised: 26th August, 2026 | Accepted: 30th August, 2026 | Available Online: 2nd September, 2026

(DOI): 10.70102/AEJ.2026.18.4s.80

1. Introduction

Climate change has emerged as a major challenge to global agriculture because of its influence on temperature, precipitation, humidity, atmospheric composition, and the frequency of extreme weather events. Agricultural ecosystems are particularly sensitive to these changes because crop growth, pest populations, disease development, and ecological interactions are strongly controlled by climatic conditions. Increasing temperatures and changing rainfall patterns can alter the geographical distribution, reproduction, survival, migration, and seasonal activity of agricultural pests [1]. Consequently, pest management strategies developed under relatively stable climatic conditions may become less effective as environmental conditions continue to change.

1.1 Background and Context

Agricultural pests are responsible for substantial losses in crop productivity and quality throughout the world. Insects, mites, weeds, plant pathogens, and other harmful organisms interact continuously with crops and their surrounding environment. Temperature, moisture availability, rainfall, and seasonal conditions influence these interactions. Climate change can therefore modify existing pest pressures while simultaneously creating suitable environmental conditions for pests to establish in regions where they were previously uncommon [2].

Rising temperatures may accelerate pest development, shorten generation intervals, increase the number of generations within a growing season, and extend periods of biological activity. Warmer winters can also improve the overwintering survival of certain pest species. At the same time, variations in rainfall and humidity can influence pest reproduction, host availability, disease transmission, and population establishment. These changes collectively contribute to increasingly dynamic pest–crop relationships.

1.2 Climate Change and Agricultural Ecosystems

Climate change affects agricultural ecosystems through both direct and indirect mechanisms. Direct effects include temperature stress, altered water availability, drought, flooding, and changes in growing-season duration. Indirect effects occur through modifications in soil properties, vegetation patterns, crop physiology, pollinator activity, pest populations, and natural enemy communities. Such interconnected effects can disturb the ecological balance that traditionally regulates pest populations [3]. Elevated atmospheric carbon dioxide may also modify crop physiology and nutritional composition, potentially influencing herbivore feeding behaviour and plant resistance mechanisms. Furthermore, extreme climatic events can weaken crops and increase their susceptibility to pest infestation. Agricultural landscapes may consequently experience new combinations of crops, pests, pathogens, and beneficial organisms, making crop protection increasingly complex.

1.3 Changing Pest Dynamics and Crop Vulnerability

Shifting climatic conditions can significantly alter pest distribution and population dynamics. Pest species previously restricted by low temperatures may expand toward higher latitudes or elevations as climatic barriers weaken. Similarly, changes in seasonal temperature patterns can modify pest emergence and synchronize or desynchronize pest activity with sensitive stages of crop development [4]. Crop vulnerability may increase when climatic stress and pest pressure occur simultaneously. Drought-stressed or heat-stressed crops can exhibit reduced physiological resistance, while rapidly reproducing pest populations may exploit these weakened conditions. Climate-driven changes can also influence natural predators, parasitoids, and other biological control organisms. If pest populations respond more rapidly to warming than their natural enemies, ecological regulation may decline and outbreaks may become more frequent.

These developments create additional challenges for conventional crop protection. Increased pest pressure may encourage greater pesticide application, potentially increasing production costs, pesticide resistance, environmental contamination, and risks to beneficial organisms. Sustainable agriculture therefore requires pest management approaches capable of adapting to changing ecological and climatic conditions.

1.4 Research Motivation and Objectives

Understanding the relationship between climate change and shifting pest dynamics is essential for developing sustainable and climate-resilient agricultural systems. Traditional pest management generally relies on historical pest distributions, seasonal calendars, field observations, and established intervention thresholds. Rapid climatic changes can reduce the reliability of these assumptions by altering when, where, and at what intensity pests occur.

The present study therefore examines how changing climatic conditions influence pest ecology, geographical distribution, seasonal activity, and crop vulnerability. It further evaluates the implications of these changes for agricultural productivity, pesticide dependence, environmental sustainability, and food security. Particular emphasis is placed on sustainable crop protection approaches involving integrated pest management, biological control, climate-smart agricultural practices, digital monitoring, remote sensing, artificial intelligence, and predictive early-warning systems. Through the integration of ecological understanding with sustainable and technology-supported pest management, the study aims to provide a framework for improving agricultural resilience against emerging climate-driven pest risks.

2. Climate Change Effects on Pest Ecology and Distribution

Climate is one of the primary factors controlling the survival, development, reproduction, distribution, and seasonal activity of agricultural pests. Changes in temperature, precipitation, humidity, and extreme weather conditions can modify pest populations both directly and indirectly through their effects on crops, natural enemies, and surrounding ecosystems. As climatic conditions shift, previously established pest boundaries may change, resulting in altered infestation periods, geographic expansion, and the emergence of new pest threats. Understanding these responses is important for designing sustainable and climate-resilient crop protection strategies.

2.1 Temperature and Pest Development

Temperature strongly influences the physiological and biological processes of many agricultural pests, particularly insects whose development depends on surrounding environmental conditions. Increasing temperatures within suitable biological limits can accelerate egg development, larval growth, maturation, and reproduction. Shorter development periods may enable some pests to complete additional generations during a single cropping season, resulting in faster population growth and greater infestation pressure [5].

Warmer winter conditions may also reduce cold-related mortality and increase the survival of overwintering pest populations. Earlier spring warming can lead to earlier emergence and longer periods of pest activity. However, the effects of temperature are species-specific. Temperatures exceeding physiological tolerance limits can reduce survival, fertility, and reproductive success. Therefore, climate warming does not uniformly increase all pest populations but instead changes the ecological suitability of particular locations for different pest species.

2.2 Changes in Rainfall and Humidity Patterns

Rainfall and humidity significantly influence pest survival, host availability, reproduction, and disease development. Increased rainfall may create favourable conditions for moisture-dependent pests and plant pathogens, while excessive precipitation can sometimes reduce populations of particular insects through physical displacement or mortality. In contrast, prolonged drought may suppress some pests while creating favourable conditions for species adapted to hot and dry environments [6].

Changes in humidity can further affect egg survival, insect development, pathogen transmission, and host–pest interactions. Climatic variability can therefore produce complex pest responses depending on crop type, pest biology, soil conditions, and local agricultural practices. Irregular rainfall can additionally stress crops, potentially reducing their natural resistance to infestation and increasing vulnerability during critical growth stages.

2.3 Geographic Range Expansion and Pest Migration

Climate change can modify the geographical boundaries within which pest species can survive and reproduce. Rising temperatures may allow pests traditionally restricted to warmer regions to move toward higher latitudes and elevations. Areas that were previously unsuitable because of cold winters may gradually become favourable for pest establishment.

Changes in wind patterns, rainfall, vegetation, and cropping systems may further influence pest migration and dispersal. Migratory insects can arrive earlier or remain active for longer periods as seasonal climatic conditions change. Geographic expansion is particularly important for agricultural regions where crops have limited resistance to newly introduced pests and where farmers have little previous experience managing them [7]. Climate-driven range expansion can consequently transform localized pest problems into regional or transboundary crop protection challenges. Continuous surveillance and spatial monitoring are therefore increasingly important for identifying emerging pest zones before severe agricultural damage occurs.

2.4 Changes in Pest Life Cycles and Seasonal Activity

Climate change can alter the timing of important biological events such as emergence, reproduction, migration, dormancy, and overwintering. Earlier warming may advance pest emergence relative to historical seasonal patterns, while prolonged warm conditions can extend pest activity later into the cropping season. These changes can disrupt traditional pest calendars used to determine monitoring and control schedules [8]. An important consequence is the possibility of altered synchronization between pests and crops. Earlier pest emergence may coincide with particularly vulnerable crop stages, increasing damage even without a major increase in overall pest abundance. Conversely, mismatches may sometimes reduce pest success when suitable host plants are unavailable.

Changes in seasonal activity may also affect relationships between pests and their natural enemies. Predators and parasitoids may respond differently to temperature and seasonal cues, creating temporary periods during which pests experience reduced biological control. Such ecological mismatches can contribute to unexpected population outbreaks.

2.5 Emerging and Invasive Pest Species

Changing climatic conditions can increase the probability that introduced pest species survive and establish populations in new agricultural regions. Global trade and transportation facilitate the movement of organisms across geographic boundaries, while climate change can determine whether newly introduced species encounter suitable environmental conditions after arrival. Invasive pests are particularly challenging because they may lack effective natural enemies in newly colonized ecosystems. Local crops may also possess limited resistance, allowing populations to increase rapidly. Once established, invasive species can cause substantial economic losses and require extensive management interventions [9].

Climate change may additionally increase the importance of pest species that were previously considered minor agricultural threats. Changes in environmental suitability, cropping patterns, host availability, and competitive interactions can allow secondary pests to become economically significant. Consequently, pest management should increasingly move from reactive control toward continuous surveillance, ecological forecasting, and early detection.

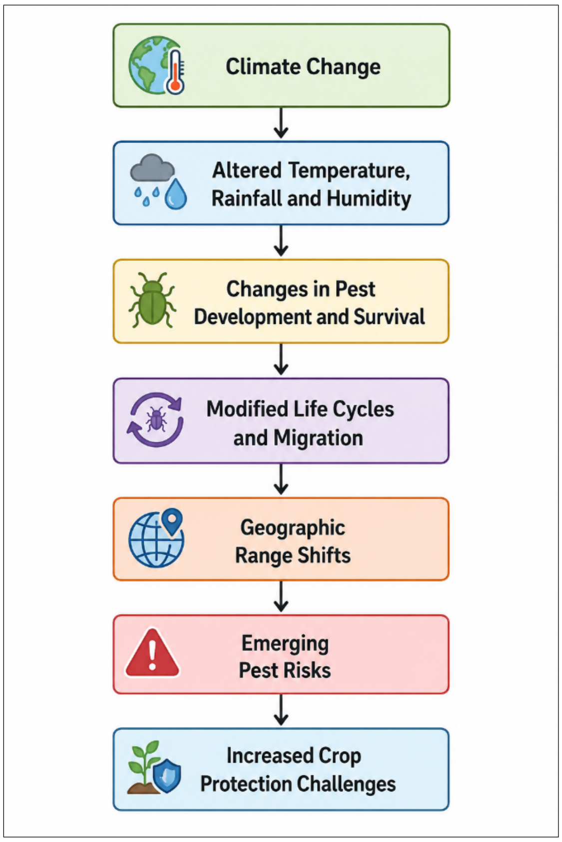

Figure 1. Climate-driven shifts in pest dynamics and crop protection challenges.

This relationship demonstrates that pest dynamics under climate change represent an interconnected ecological process rather than a response to a single climatic variable. Effective agricultural adaptation therefore requires simultaneous consideration of climate conditions, pest biology, crop vulnerability, and ecosystem interactions.

Table 1. Influence of Climate Change Factors on Agricultural Pest Ecology and Distribution

Climate Factor	Effect on Pest Ecology	Change in Pest Dynamics	Potential Agricultural Impact
Rising temperature	Accelerated growth and development	More generations and longer activity periods	Increased crop infestation and damage
Warmer winters	Reduced cold-related mortality	Greater overwintering survival	Earlier and larger pest populations
Altered rainfall	Changes survival	Population increases or	Greater variabilit

	and breeding conditions	declines depending on species	y in pest outbreaks
Increased humidity	Favourable conditions for moisture-dependent pests and pathogens	Increased reproduction and disease transmission	Higher crop infection and pest pressure
Drought conditions	Changes host quality and water availability	Advantage to heat- and drought-tolerant pests	Increased stress-related crop vulnerability
Longer warm seasons	Extends suitable developmental period	Longer pest activity and additional generations	Extended crop protection requirements
Extreme weather events	Disturbs habitats and ecological interactions	Pest displacement and redistribution	Emergence of pest problems in new areas
Geographic warming	Creates suitable habitats in previously cooler regions	Poleward and higher-elevation range expansion	Exposure of new agricultural regions
Seasonal shifts	Changes timing of emergence and migration	Altered pest–crop synchronization	Damage during sensitive crop growth stages
Ecosystem changes	Alters predators, parasitoids, and competitors	Disruption of natural pest regulation	Increased likelihood of pest outbreaks

The table 1. demonstrates that climate change affects agricultural pests through multiple interconnected mechanisms rather than through temperature increase alone [10][11]. Rising temperatures and warmer winters can accelerate pest development and improve survival, potentially increasing the number of generations within a cropping season. Changes in rainfall, humidity, and drought conditions further modify pest reproduction and host availability. Geographic warming can enable pests to establish in previously unsuitable regions, while seasonal changes may alter the synchronization between pest emergence and vulnerable crop stages. Climate-driven disruption of predators and parasitoids can additionally weaken natural biological control. These combined effects indicate the need for dynamic pest surveillance, climate-based forecasting, and adaptive integrated pest management strategies.

3. Impacts of Shifting Pest Dynamics on Agriculture

Climate-driven changes in pest distribution, abundance, development, and seasonal activity have important consequences for agricultural production. Changes in pest pressure can influence crop growth, yield, quality, production costs, pesticide use, and the stability of agricultural ecosystems. The impacts are particularly significant when climate-induced crop stress occurs simultaneously with increased pest activity. Shifting pest dynamics therefore represent not only an ecological challenge but also an important concern for sustainable agriculture and food security.

3.1 Pest–Crop Interactions under Changing Climate

Climate change can modify interactions between crops and pests by influencing both pest biology and plant physiology. Higher temperatures may accelerate pest development and feeding activity, while drought, heat stress, and irregular rainfall can reduce crop vigour and natural defence mechanisms. These simultaneous responses may increase the susceptibility of crops to infestation.

Changes in atmospheric conditions can also influence plant nutritional quality, growth patterns, and biochemical defence mechanisms. Such changes may affect pest feeding preferences, reproductive success, and host selection. Pest species capable of rapidly adapting to environmental changes may gain ecological advantages, particularly in intensive agricultural systems dominated by genetically similar crops [12].

The timing of pest attacks is equally important. Climate-induced changes in pest emergence can cause infestations to coincide with sensitive stages such as germination, flowering, fruit development, or grain formation. Even moderate pest populations occurring during these stages may cause substantial production losses.

3.2 Crop Yield and Quality Losses

Increasing pest pressure can directly reduce agricultural productivity through damage to leaves, stems, roots, flowers, fruits, and seeds. Defoliating insects reduce photosynthetic capacity, while sap-feeding pests interfere with nutrient transport and plant growth. Root-feeding pests can restrict water and nutrient uptake, whereas fruit- and seed-feeding species directly reduce marketable production.

Climate-driven pest outbreaks may also affect crop quality. Physical damage can reduce appearance, storage life, nutritional value, and commercial acceptability. Pest injuries can additionally provide entry points for secondary pathogens, increasing the possibility of combined pest and disease damage [13].

Changes in the geographic distribution of pests can expose crops in previously unaffected regions to new biological threats. Such agricultural systems may have limited resistant varieties, monitoring infrastructure, or management experience. Consequently, emerging pest problems can produce disproportionately high losses during the initial stages of establishment.

3.3 Changes in Pest–Natural Enemy Relationships

Natural enemies, including predators, parasitoids, and entomopathogenic organisms, provide important ecological regulation of agricultural pest populations. Climate change may alter these relationships because pests and their natural enemies do not necessarily respond to environmental changes at the same rate [14].

For example, increasing temperatures may cause a pest to emerge earlier in the growing season while its principal predator or parasitoid retains a different seasonal response. This temporal mismatch can create periods in which pest populations increase with limited natural regulation. Changes in rainfall and humidity may similarly influence the survival and effectiveness of beneficial organisms.

Geographic shifts may further separate pests from their established natural enemies. When pests expand into new agricultural regions, suitable predators or parasitoids may not be present. This ecological release can facilitate rapid population growth and increase the likelihood of severe outbreaks. Protecting beneficial organisms and strengthening biological control are therefore important components of climate-resilient pest management.

3.4 Increased Pesticide Dependence and Environmental Risks

Greater pest pressure and unpredictable outbreaks may encourage farmers to increase the frequency or intensity of pesticide applications. Although chemical control can provide rapid suppression, excessive dependence on pesticides can create economic, environmental, and ecological challenges.

Frequent pesticide exposure increases selection pressure for resistant pest populations. Over time, previously effective compounds may become less reliable, requiring higher application rates, alternative chemicals, or more frequent treatments. This process can increase production costs and complicate long-term pest management [15].

Excessive pesticide application may also affect non-target organisms, including pollinators, predators, parasitoids, soil organisms, and aquatic species. Pesticide residues can enter soil and water systems through runoff, leaching, and spray drift. Furthermore, the destruction of natural enemies can weaken biological pest regulation and contribute to pest resurgence or secondary pest outbreaks.

Climate change can further influence pesticide effectiveness. Higher temperatures, rainfall events, and altered pest behaviour may affect pesticide persistence, application timing, and exposure. Sustainable crop protection therefore requires reducing unnecessary chemical applications and integrating multiple complementary pest management approaches.

3.5 Food Security and Socioeconomic Implications

The consequences of shifting pest dynamics extend beyond individual farms. Increasing crop losses can reduce food availability, affect commodity prices, and create instability within agricultural supply chains. Regions dependent on climate-sensitive crops may experience greater vulnerability when pest outbreaks coincide with drought, heat waves, floods, or other climatic stresses [16].

Smallholder farmers can be particularly affected because they may have limited access to pest monitoring technologies, resistant crop varieties, biological control products, forecasting services, and financial resources. Increased pesticide expenditure and repeated crop losses can reduce farm profitability and household income [17].

Changing pest distributions may also require governments and agricultural organizations to strengthen surveillance, quarantine, extension services, and regional cooperation. Transboundary pests can move across administrative and national borders, making coordinated monitoring and early-warning systems increasingly important.

Table 2. Agricultural Implications of Climate-Driven Shifts in Pest Dynamics

Shifting Pest Dynamic	Major Agricultural Effect	Crop Protection Implication	Sustainability Concern
Increased pest abundance	Greater feeding and crop damage	More frequent monitoring and control	Higher input requirements
Earlier pest emergence	Pest attack during sensitive crop stages	Adjustment of intervention timing	Reduced effectiveness of traditional pest calendars
Longer pest activity	Extended infestation period	Longer crop protection period	Increased management costs
Additional pest generations	Rapid population buildup	Repeated management interventions	Greater risk of pesticide dependence
Geographic range expansion	Introduction of pests into new production areas	Expanded surveillance and quarantine	Threat to previously unaffected ecosystems
Invasive pest establishment	Severe damage from unfamiliar pest species	Early detection and rapid response	Ecological disruption
Pest–natural enemy mismatch	Reduced biological regulation	Greater need for biological control management	Loss of ecosystem-based pest suppression
Increased pesticide use	Short-term pest suppression	Resistance management becomes necessary	Residues, non-target effects, and pollution
Climate-stressed crops	Increased susceptibility to pest attack	Combined crop and pest stress management	Yield instability
Frequent pest outbreaks	Yield and quality losses	Climate-based forecasting and IPM	Food security and economic risks

Table 2 shows that shifting pest dynamics can affect agriculture through increased pest abundance, altered seasonal activity, geographic expansion, and disruption of natural biological control. Earlier emergence and additional pest generations can increase crop exposure and require changes in conventional pest-management schedules [18]. Geographic expansion and invasive species create additional surveillance and quarantine requirements, particularly in regions with limited previous exposure to such pests. Increased reliance on pesticides may provide immediate control but can contribute to resistance, environmental contamination, and adverse effects on beneficial organisms [19]. Therefore, climate-resilient agriculture requires integrated approaches combining pest surveillance, forecasting, biological control, resistant crop varieties, and adaptive integrated pest management.

4. Sustainable Pest Management and Climate-Resilient Crop Protection

Climate-driven changes in pest distribution, population growth, seasonal activity, and crop vulnerability require pest management systems that are adaptive, environmentally sustainable, and capable of responding to emerging risks. Conventional approaches based primarily on scheduled pesticide application may become increasingly ineffective when pest occurrence becomes spatially and temporally unpredictable. Sustainable crop protection therefore requires the integration of ecological management, biological control, climate-smart practices, digital technologies, and predictive pest monitoring [20]. Such an integrated strategy can reduce crop losses while limiting environmental impacts and excessive dependence on chemical pesticides.

4.1 Integrated Pest Management under Climate Change

Integrated Pest Management (IPM) provides an important foundation for climate-resilient crop protection by combining biological, cultural, mechanical, genetic, and chemical control measures. Rather than applying pesticides according to fixed schedules, IPM emphasizes pest monitoring and intervention when pest populations reach economically significant levels.

Under changing climatic conditions, conventional IPM practices need to incorporate climate information. Temperature, rainfall, humidity, crop growth stage, and historical pest observations can be jointly evaluated to estimate potential pest development and outbreak risk. Monitoring systems should also account for earlier pest emergence, longer activity periods, additional generations, and geographic range expansion.

Crop rotation, field sanitation, adjustment of planting dates, resistant varieties, trap crops, and habitat management can further reduce pest establishment. Chemical pesticides can remain part of IPM but should be applied selectively and only when necessary. This approach can reduce pesticide residues, protect beneficial organisms, slow resistance development, and improve long-term agricultural sustainability.

4.2 Biological and Ecological Pest Control

Biological control uses natural enemies such as predators, parasitoids, and microbial agents to regulate pest populations. It is particularly valuable under climate change because it reduces dependence on synthetic pesticides while supporting ecosystem-based pest regulation.

Climate change, however, can affect biological control by altering relationships between pests and their natural enemies. Differences in temperature tolerance, seasonal emergence, and geographic movement may create mismatches between pest populations and beneficial organisms. Climate-resilient biological control therefore requires identification of natural enemies capable of functioning effectively under changing environmental conditions.

Ecological approaches can complement biological control through conservation of natural habitats, flowering vegetation, field margins, and landscape diversity. Such environments provide shelter and food resources for beneficial organisms. Maintaining ecological diversity can strengthen natural pest suppression and improve the resilience of agricultural ecosystems.

4.3 Climate-Smart Agricultural Practices

Climate-smart agricultural practices can reduce crop vulnerability while simultaneously improving adaptation to environmental stress. Crop diversification, intercropping, crop rotation, conservation agriculture, improved soil management, and appropriate irrigation practices can create agricultural systems that are less favourable for rapid pest establishment.

Adjustment of sowing and harvesting periods may help avoid periods of peak pest activity. Resistant and climate-tolerant crop varieties can provide additional protection when heat, drought, and pest pressure occur simultaneously. Diversified cropping systems may also interrupt pest life cycles and reduce the availability of continuous host resources.

Soil health is another important component of resilient crop protection. Improved organic matter, water retention, and nutrient availability can strengthen crop growth and increase tolerance to pest damage. Thus, climate-smart crop management should integrate climate adaptation with ecological pest prevention rather than treating these challenges separately.

4.4 AI, Remote Sensing, and Digital Pest Monitoring

Digital technologies provide new opportunities for detecting and monitoring climate-driven changes in pest populations. Field sensors, weather stations, smart traps, satellite observations, unmanned aerial vehicles, mobile applications, and Internet of Things devices can generate continuous information about environmental conditions, crop health, and pest occurrence. Remote sensing can identify changes in crop vegetation, canopy condition, moisture stress, and spatial patterns potentially associated with pest damage. Drone and field imagery can provide higher-resolution observations for localized monitoring. Geographic Information Systems can integrate these observations with climate and pest data to identify spatial hotspots and emerging risk zones.

Artificial intelligence and machine learning can process large volumes of heterogeneous agricultural data to recognize patterns that may be difficult to identify through manual observation. Classification models can identify pests or categorize infestation severity, while predictive models can estimate future outbreak probability based on climatic and ecological variables. Digital monitoring therefore supports a transition from periodic field inspection toward continuous and data-driven pest surveillance.

4.5 Predictive Pest Risk Assessment and Early Warning Systems

Early-warning systems are increasingly important as historical pest calendars become less reliable under climate change. Predictive pest risk assessment can combine current and historical information on temperature, rainfall, humidity, crop condition, pest observations, and geographic characteristics to estimate where and when pest outbreaks are likely to occur.

The basic predictive process can be represented as:

Climate and Crop Data → Pest Monitoring Data → Data Integration → AI-Based Pest Prediction → Spatial Risk Assessment → Early Warning → Targeted Pest Management

Forecasts can classify agricultural areas into low-, moderate-, or high-risk zones and provide farmers with advance information for field inspection and preventive management. Spatial pest-risk maps can further help agricultural agencies prioritize surveillance and resource allocation.

Early warnings can reduce unnecessary pesticide applications because interventions can be concentrated in locations and periods with elevated pest risk. However, reliable forecasting requires representative datasets, continuous monitoring, local validation, and periodic model updating as climatic and ecological conditions change.

4.6 Sustainable Crop Protection Framework

An effective climate-resilient crop protection framework should integrate ecological knowledge with climate observations and digital technologies. Climate and weather information can first be combined with crop, pest, soil, and environmental data. These observations can then be processed to identify changing pest patterns and estimate future infestation risks.

AI-based prediction and GIS-based spatial assessment can identify potential pest hotspots, while IPM and biological control principles can guide appropriate management responses. Human expertise remains important for verifying model predictions and selecting interventions appropriate to local agricultural conditions.

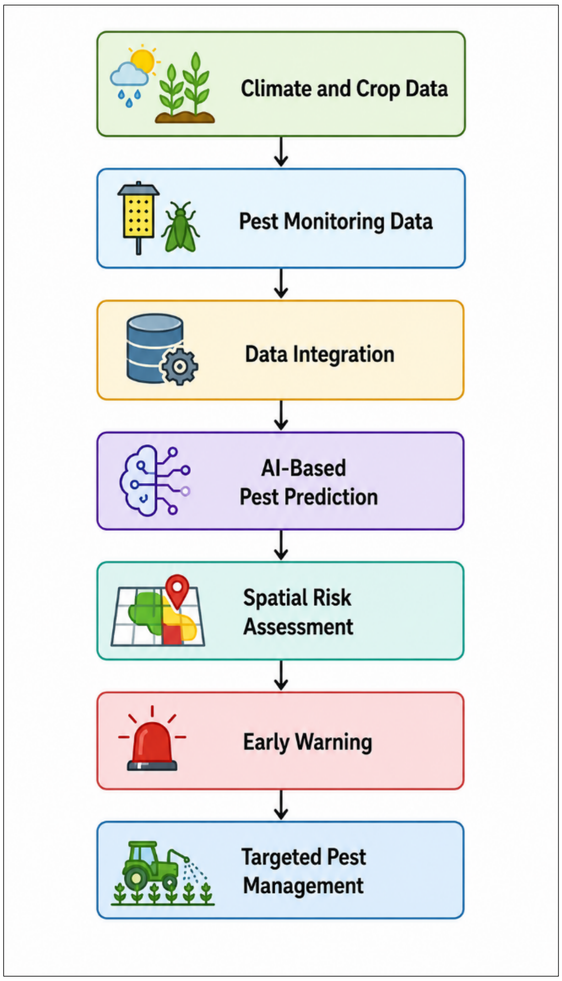

Figure 2. AI-based predictive framework for pest risk assessment and targeted management.

This framework shifts crop protection from reactive pest suppression toward predictive and preventive management. The integration of climate-smart agriculture, ecological pest regulation, digital monitoring, and targeted intervention can improve crop resilience while reducing pesticide dependence and environmental impacts.

Table 3. Climate-Resilient and Sustainable Pest Management Strategies

Strategy	Primary Function	Climate-Resilient Application	Sustainability Benefit
Integrated Pest Management	Combines multiple control approaches	Adapts interventions to changing pest pressure	Reduces unnecessary pesticide use

Biological control	Uses natural enemies	Supports ecological regulation of emerging pests	Protects ecosystem functions
Resistant crop varieties	Reduces crop susceptibility	Improves tolerance to combined climatic and pest stress	Reduces chemical inputs
Crop diversification	Disrupts pest establishment	Improves resilience to changing pest populations	Enhances agroecosystem diversity
Climate-smart practices	Adjusts cultivation to climate risks	Modifies sowing, irrigation, and crop management	Improves overall farm resilience
Smart pest traps and IoT	Enables continuous pest surveillance	Detects changing pest activity in real time	Supports timely intervention
Remote sensing and GIS	Detects and maps crop stress	Identifies emerging pest-risk zones	Enables site-specific management
AI-based prediction	Forecasts pest occurrence and severity	Integrates climate and pest patterns	Supports preventive crop protection
Early-warning systems	Provides advance outbreak alerts	Responds to changing seasonal pest patterns	Reduces crop losses and excessive spraying
Targeted pesticide application	Controls economically significant infestations	Focuses treatment on high-risk areas	Minimizes environmental contamination

The comparative assessment indicates that no single pest management strategy is sufficient to address climate-driven pest risks. Ecological approaches provide long-term sustainability, whereas AI, remote sensing, and IoT technologies improve the speed and precision of pest detection. Their integration with IPM enables management decisions to be based on actual or predicted risk rather than routine pesticide schedules. Such a combined approach provides a practical pathway toward sustainable and climate-resilient crop protection.

5. Conclusion and Future Directions

Climate change is progressively reshaping agricultural pest dynamics by altering pest development, survival, reproduction, migration, geographical distribution, and seasonal activity. Rising temperatures, changing rainfall and humidity patterns, warmer winters, drought conditions, and extreme climatic events can create favourable environments for some pest species while modifying established pest–crop and pest–natural enemy relationships. These changes can result in earlier pest emergence, additional generations, longer infestation periods, geographic range expansion, and the establishment of invasive and emerging pests. Consequently, agricultural production systems may experience increased crop vulnerability, yield and quality losses, greater management costs, and additional risks to food security. The findings emphasize that conventional pest management based primarily on historical pest calendars and routine pesticide application may be insufficient under increasingly variable climatic conditions. Greater pesticide dependence can further contribute to pest resistance, environmental contamination, biodiversity loss, and adverse effects on pollinators and natural enemies. Sustainable crop protection therefore requires a transition toward adaptive and integrated pest management. Biological control, resistant crop varieties, crop diversification, improved soil and water management, adjusted planting schedules, and other climate-smart agricultural practices can strengthen ecological resilience while reducing unnecessary chemical inputs. Digital technologies can further improve the capacity of agricultural systems to respond to shifting pest risks. Artificial intelligence, machine learning, Internet of Things sensors, smart pest traps, remote sensing, unmanned aerial vehicles, and Geographic Information Systems can support continuous pest surveillance, spatial risk mapping, outbreak prediction, and early-warning mechanisms. Integrating these technologies with climate information and field observations can facilitate targeted interventions before pest populations reach damaging levels.

Future research should focus on developing region-specific pest forecasting models that incorporate long-term climate projections, crop characteristics, pest biology, and ecological interactions. Greater attention is also required toward understanding climate-induced changes in invasive pests, natural enemies, pesticide resistance, and multi-pest interactions. Standardized datasets, long-term field observations, explainable AI models, and affordable digital monitoring technologies should be developed to improve accessibility for smallholder farmers. Ultimately, combining ecological pest management with climate-smart agriculture and predictive digital technologies offers a sustainable pathway for protecting crops, reducing environmental impacts, and strengthening agricultural resilience under future climate conditions.

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